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Generation of a 640 Gbit/s NRZ OTDM signal using a silicon microring resonator

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Abstract: A 640 Gbit/s NRZ OTDM signal has been successfully generated for the first time by format conversion of a 640 Gbit/s OTDM signal from RZ to NRZ. First, a coherent 640 Gbit/s OTDM RZ signal is generated by wavelength conversion of the original incoherent OTDM signal utilizing Kerr switching in a highly nonlinear fiber. Second, RZ-to-NRZ format conversion is achieved in a specially designed silicon microring resonator with FSR of 1280 GHz, Q value of 638, high extinction ratio and low coupling loss to optical fiber. A 640 Gbit/s NRZ OTDM signal with very clear eye-diagram and narrower bandwidth than both the original incoherent 640 Gbit/s and the wavelength converted coherent 640 Gbit/s RZ OTDM signals has been obtained. Bit error ratio measurements show error free ($<10^{-9}$) performance at a received power of -30 dBm for all the OTDM channels of the 640 Gbit/s NRZ signal, with very low power penalty (<0.5 dB) and improved dispersion tolerance compared to the wavelength converted RZ case.

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Introduction

Optical time division multiplexing (OTDM) is an essential multiplexing technique potentially allowing symbol rates beyond the limits currently achievable by electronic multiplexing. By bit-interleaving a large number of optical data tributaries at the same wavelength, symbol rates exceeding 1 Terabaud have been recently reported [1]. An OTDM signal is typically demultiplexed in an optical gate controlled by a clock signal consisting of short pulses at a repetition frequency corresponding to the base rate. However, since the pulse width of the OTDM signal is fairly narrow, the OTDM signal demultiplexing is very sensitive to timing jitter. To release such timing jitter sensitivity, a flat top pulse may be used to control the optical gate [2]. Furthermore, due to the use of short return-to-zero (RZ) pulses required by OTDM, the signal spectrum bandwidth is very broad, making the OTDM signals extremely sensitive to dispersion as well as spectrally inefficient. Ultra-high-speed signals modulated in the non return-to-zero (NRZ) format would alleviate those issues, resulting in increased timing jitter tolerance in the demultiplexing process thanks to their flat top, as well as better resilience to dispersion and enhanced spectral efficiency [3]. However, the generation of high-speed NRZ signals is limited by the speed of electrical multiplexers (values as high as 165 Gbit/s have been reported [4]) and by the bandwidth of electro-optic modulators. Here, we propose instead to generate an ultra high speed NRZ signal using conventional OTDM techniques followed by all-optical modulation format conversion from RZ to NRZ, which can be performed in a silicon microring resonator (MRR), as recently demonstrated for moderate data rates in wavelength division multiplexing (WDM) applications [5].

In this work, a 640 Gbit/s NRZ OTDM signal is successfully generated by converting the format of an OTDM signal from RZ to NRZ utilizing a single silicon MRR with a free-spectral-range (FSR) of 1280 GHz and a Q value of 638. Kerr switching in a highly nonlinear fiber (HNLF) is first applied to wavelength convert the original incoherent 640 Gbit/s OTDM signal to a coherent 640 Gbit/s RZ signal. After the RZ-to-NRZ format conversion in the silicon MRR, a 640 Gbit/s NRZ OTDM signal with very clear eye-diagram and narrower bandwidth than both the original incoherent 640 Gbit/s and wavelength converted coherent 640 Gbit/s RZ signals is obtained. To the best of our knowledge, this is the highest bit rate optical signal ever generated in the NRZ format. Bit error rate (BER) measurements show very good performances for all the OTDM channels of the 640 Gbit/s NRZ signal, and improved dispersion tolerance compared to the wavelength converted RZ-OTDM signal.

Principle and optimization

The method to generate the 640 Gbit/s NRZ signal is based on format conversion of the 640 Gbit/s OTDM signal from the RZ to the NRZ format utilizing optical spectrum transformation [5]. In a typical OTDM signal, the phases of the different tributary channels are uncorrelated, making the OTDM signal pulse-to-pulse incoherent. To correctly perform the RZ-to-NRZ format conversion, a coherent RZ OTDM signal at 640 Gbit/s is required, which can be obtained by wavelength converting the original incoherent OTDM signal, for instance using Kerr switching in a piece of highly nonlinear fiber (HNLF) [6]. After wavelength conversion, a coherent 640 Gbit/s RZ spectrum with strong first order harmonic components is obtained. The periodic notch filtering characteristic of the through transmission of a MRR can then be used to suppress the first order harmonic components of

the spectrum, thus realizing RZ-to-NRZ format conversion. Residual amplitude ripples in the converted NRZ signal can be further reduced by an additional optical bandpass filter (OBPF) [5, 7]. To effectively perform 640 Gbit/s RZ-to-NRZ format conversion, a MRR with FSR of 1280 GHz (corresponding to twice the bit rate of the signal [5]) is required. For good format conversion, both high Q factor (defined as $Q = (I_1 - I_0) / (\sigma_0 + \sigma_1)$, where I_0 and I_1 are the means and σ_0 and σ_1 denote the standard deviations of the detected photocurrent for the logic “zero” and “one” levels, respectively [8]) and low amplitude ripples are required for the converted signal. Figures 1(a) and 1(b) show the simulated amplitude ripples and Q factor of the converted 640 Gbit/s NRZ signal as a function of the Q value of the MRR (defined as the ratio of the centre frequency of a resonance to its 3-dB bandwidth) and the OBPF 3 dB bandwidth. The OBPF is modeled as a 1st order Gaussian type filter. The amplitude ripple is defined as the ratio between the maximum power deviation and the average power of the high level [5]. One can find optimum regions for bandwidths of the OBPF and Q values of the MRR, which are denoted by the ellipses in Figs. 1(a) and 1(b). An MRR with Q value around 550, and an OBPF with a bandwidth around 600 GHz will result in the best RZ-to-NRZ format conversion with high Q factor and low amplitude ripples.

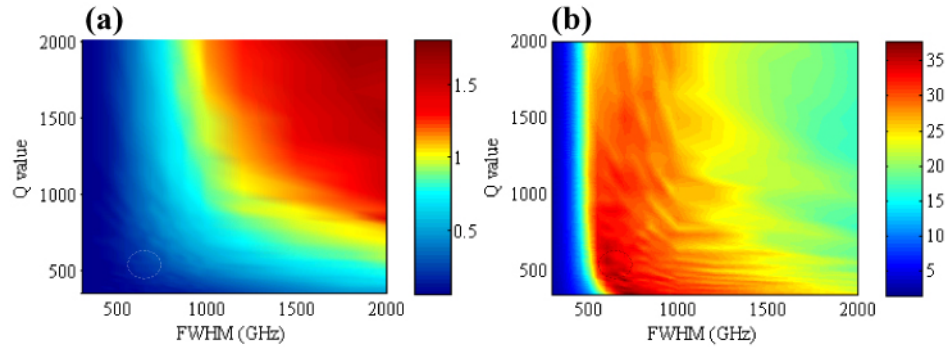


Fig. 1. (a) Amplitude ripples and (b) Q factor of the converted NRZ signal versus Q value of the MRR and bandwidth of the OBPF for 640 Gbit/s RZ-to-NRZ format conversion.

Device fabrication

The silicon MRR was fabricated on a silicon-on-insulator (SOI) wafer with top silicon thickness of 250 nm and buried silicon dioxide of 3 μm . First, diluted (1:1 in anisole) electron-beam resist ZEP520A was spin-coated on the wafer to form a ~ 110 nm-thick mask layer. The structure of the device was then defined using electron-beam lithography (JEOL JBX-9300FS). After that, the sample was etched by inductively coupled plasma reactive ion etching (ICP-RIE) to transfer the patterns to the top silicon layer. A layer of 600 nm thick benzocyclobutene (BCB) is used to cover the waveguide and form the upper cladding layer to protect the device. After that, a layer of 3.5 μm thick polymer (SU8-2005) was spin-coated on top of the BCB layer. The nano-couplers are defined by electron-beam lithography, and finally formed after developing. The radius of the MRR is 9.2 μm , as shown in Fig. 2(a), with

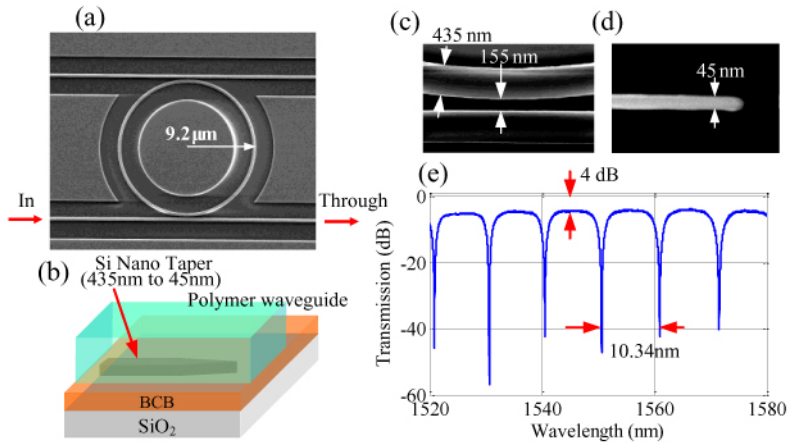


Fig. 2. (a) Scanning electron microscope (SEM) picture of the fabricated silicon microring resonator. (b) Design of the nano-taper coupler. (c), (d) SEM pictures of the coupling region and the nano-taper. (e) Measured through transmission for the TM_0 mode of the fabricated MRR.

a waveguide width of 435 nm and coupling gap of 155 nm for both through and drop coupling regions, as shown in Fig. 2(c). The silicon waveguide is inversely tapered to 45 nm, covered by a polymer waveguide (see Figs. 2(b) and 2(d)) to form a nano-coupler, resulting in ultra-low coupling loss [9] to the fiber. Figure 2(e) shows the measured through transmission of the MRR as a function of wavelength for the TM_0 mode. The extinction ratio (ER) of the through transmission is as high as 40 dB. The extinction ratios appear different for the different resonances, potentially due to the limited wavelength resolution of the optical spectrum analyzer used for the measurement of the transfer function. The measured FSR is 10.34 nm, corresponding to 1280 GHz, and the Q value is 638, which all agree very well with our design requirements. The total insertion loss of the device is only ~ 4 dB. As is generally the case for silicon nano-waveguides, the transmission of the device is polarization dependent. A polarization diversity structure can be introduced to reduce the polarization dependence [10-11].

Experimental results

Figure 3 shows the experimental setup for 640 Gbit/s NRZ OTDM signal generation. A 640 Gbit/s RZ OTDM signal at 1560 nm is generated in a delay line multiplexer from a 10 GHz optical clock that has been first intensity modulated at the 10 Gbit/s base rate with a 2^7-1 pseudo random binary sequence (PRBS). The time multiplexing operation is PRBS preserving for this pattern length. The 640 Gbit/s RZ OTDM signal is first wavelength converted using a Kerr switch. For this purpose, the signal is amplified using an erbium-doped fiber amplifier (EDFA) and coupled together with an amplified CW probe at 1535.6 nm in a 200 m HNLF (nonlinear coefficient: $10 \text{ W}^{-1} \cdot \text{km}^{-1}$; zero dispersion wavelength: $\lambda_0=1552 \text{ nm}$; dispersion slope: $0.011 \text{ ps}/(\text{nm}^2 \cdot \text{km})$). The states of polarization (SOP) of the signal and pump are optimized using polarization controllers (PCs). OBPFs with bandwidths of 12 and 13 nm (signal) and 1.3 nm (pump) are used to filter out the amplified spontaneous emission (ASE) introduced by the EDFAs. A polarisation beam splitter (PBS) then transmits the SOP of the CW probe that has been rotated by the signal in the HNLF, hence resulting in 640 Gbit/s wavelength conversion to a pulse-to-pulse coherent signal. Short pieces (2 or 3 m long) of dispersion compensating fiber (DCF) with dispersion parameter of $-90.7 \text{ ps}/(\text{nm} \cdot \text{km})$ and dispersion slope of $-0.326 \text{ ps}/(\text{nm}^2 \cdot \text{km})$ are used to compensate the dispersion, mostly introduced by the EDFAs, throughout the set-up, thus preventing excessive broadening of the pulses. The converted RZ signal is then amplified before being input to the MRR in order to

perform format conversion. A PC and a polarizer (pol.) are used to align its SOP with the TM mode of the silicon waveguide. Two cascaded OBPFs with bandwidths of 9 and 5 nm are then used to reduce the amplitude ripples of the converted NRZ signal. Finally, the 640 Gbit/s

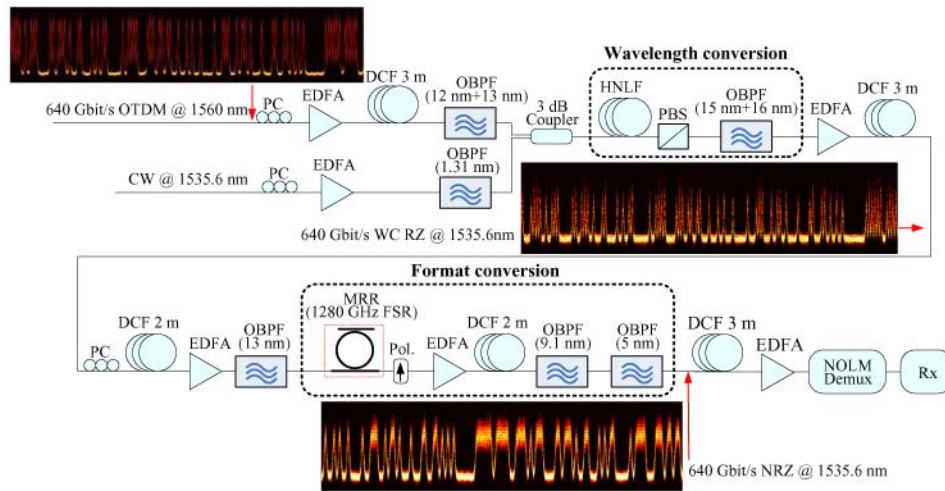


Fig. 3. Experimental setup for 640 Gbit/s RZ-to-NRZ format conversion. The insets show optical sampling oscilloscope traces of the original incoherent 640 Gbit/s OTDM signal, 640 Gbit/s wavelength converted RZ signal, as well as the 640 Gbit/s format converted NRZ signal.

NRZ OTDM signal is time-demultiplexed in a nonlinear optical loop mirror (NOLM) [12] before being detected in a 10 Gbit/s receiver.

Figure 4(a) illustrates the spectrum transformation of the 640 Gbit/s NRZ signal generation. Due to the lack of pulse-to-pulse phase correlation between the tributary channels of the original 640 Gbit/s OTDM signal, one can find that the OTDM spectrum (blue) does not contain strong harmonic components at multiples of frequencies corresponding to the bit rate. However, the 640 Gbit/s wavelength converted RZ spectrum (purple) displays clear and strong harmonic components and is thus suitable for format conversion in the MRR. For this purpose, the first order harmonic components of the 640 Gbit/s wavelength converted RZ spectrum are aligned with the notches of the through transmission (green) of the MRR. After the OBPF, a 640 Gbit/s NRZ spectrum (black), whose first order harmonic components have been effectively suppressed, is obtained, showing a reduced bandwidth compared to the 640 Gbit/s wavelength converted RZ spectrum. Figures 4(b) to 4(d) show the corresponding eye-diagrams, measured using an optical sampling oscilloscope with 1 ps resolution, of the 640 Gbit/s original OTDM, wavelength converted RZ, and format converted NRZ signals, respectively. A very clear eye diagram with low amplitude ripple is obtained for the 640 Gbit/s NRZ signal.

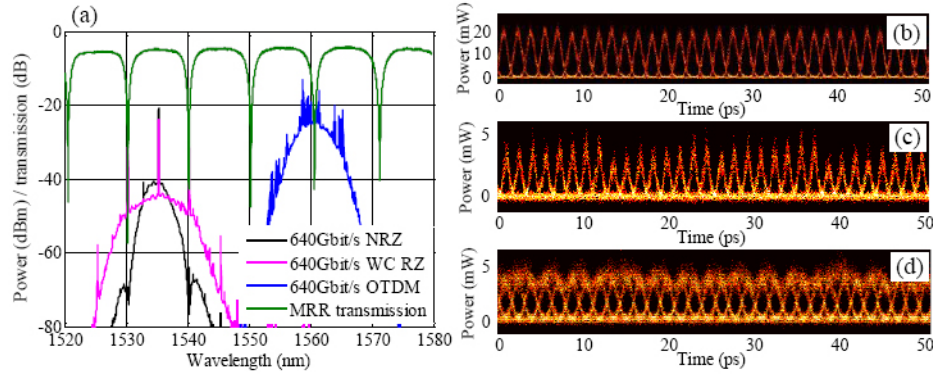


Fig. 4. (a) Spectra of the original OTDM (blue), wavelength converted RZ (purple), and format converted NRZ signals (black), as well as through transmission of the silicon microring resonator (green). (b)–(d) eye diagrams of the original 640 Gbit/s incoherent OTDM, wavelength converted 640 Gbit/s coherent RZ OTDM, and format converted 640 Gbit/s NRZ signals, respectively.

BER measurements are performed on typical 10 Gbit/s tributaries demultiplexed from the 640 Gbit/s wavelength converted RZ signal and the 640 Gbit/s NRZ signal. The resulting BER curves are shown in Fig. 5(a). One can find that the four channels demultiplexed from the 640 Gbit/s NRZ signal perform very similarly to the 640 Gbit/s wavelength converted RZ signal, without notable power penalty and error floor. Note that the four channels are direct neighbours. The BER performances are the same for the tributaries demultiplexed from the 640 Gbit/s NRZ signal when using PRBS lengths of 2^7-1 and $2^{31}-1$, hinting towards a reduced pattern sensitivity of the format conversion process. It should however be stated that the time multiplexing scheme employed in this work is not pattern preserving at $2^{31}-1$. Even though it can be seen in Fig. 4(a) that the wavelength conversion has resulted in a broadening of the RZ signal spectrum, the dispersion tolerance of the 640 Gbit/s NRZ signal is compared to that of the wavelength converted RZ signal since both signals exhibit pulse-to-pulse coherence and are at the same wavelength. In order to perform this comparison, short pieces of DCFs are added before demultiplexing. The resulting BER curves are also shown in Fig. 5(b). Good BER performance with power penalty as low as ~ 1.5 dB is obtained for the tributary demultiplexed from the 640 Gbit/s NRZ signal after 1 m DCF transmission. For the same DCF length, an error floor is present in the case of the 640 Gbit/s wavelength converted RZ signal. A similar error-floor appears for the 640 Gbit/s NRZ signal after transmission over 4 m DCF. Hence, it is clear that the 640 Gbit/s NRZ signal exhibits improved dispersion tolerance compared to the wavelength converted RZ signal. Figure 6 shows that BER below 10^{-9} can be obtained for all the 64 OTDM tributaries demultiplexed from the 640 Gbit/s NRZ signal. The procedure was to optimize the system until a BER better than 10^{-9} could be reached with a fixed receiver power of -30 dBm, potentially resulting in suboptimum operation of some channels compared to Fig. 5(a). All 64 channels exhibit error free performance (BER below 10^{-9}), showing the very good performance of the 640 Gbit/s NRZ signal. It should be noticed that, in all BER measurements, the receiver power is measured after demultiplexing. Consequently, all BER characterisations are performed on RZ waveforms, which explains why the sensitivities of the NRZ and RZ formats do not differ significantly.

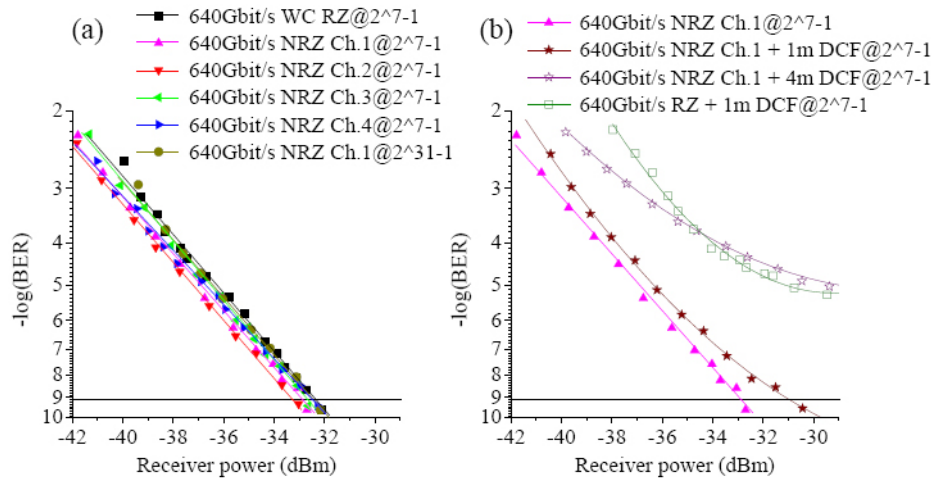


Fig. 5. (a) BER measurement of the demultiplexed signal from 640 Gbit/s wavelength converted RZ with PRBS length of 2^7-1 , four neighbouring channels demultiplexed from 640 Gbit/s NRZ with PRBS length of 2^7-1 , as well as channel 1 demultiplexed from 640 Gbit/s NRZ with PRBS length $2^{31}-1$. (b) BER results with PRBS length of 2^7-1 for channel 1 demultiplexed from 640 Gbit/s NRZ with 1 and 4 m DCFs, and a demultiplexed tributary from the 640 Gbit/s wavelength converted RZ signal with 1 m DCF.

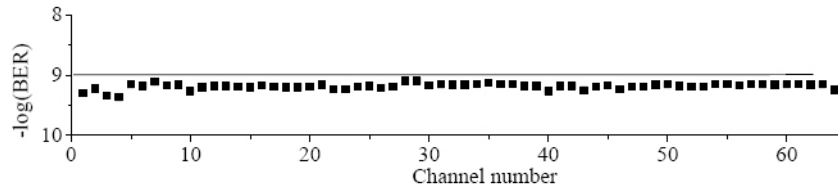


Fig. 6. Verification that all 64 OTDM tributaries demultiplexed from the 640 Gbit/s NRZ signal exhibit error free performance at a receiver power of -30 dBm.

Conclusion

A 640 Gbit/s NRZ OTDM signal has been successfully generated for the first time by performing RZ-to-NRZ format conversion of a 640 Gbit/s RZ OTDM signal using a silicon microring resonator with FSR of 1280 GHz, Q value of 638, high extinction ratio and low coupling loss to optical fiber. Bit error rate measurements show very good performance for all the OTDM tributaries of the 640 Gbit/s NRZ signal, and improved dispersion tolerance compared to the wavelength converted RZ OTDM signal.

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